

HYBRID LZW COMPRESSION

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Abstract:

The Science Data Management and Science Payload Operations subpanel reports from the NASA Conference on Scientific Data Compression (Snowbird, Utah in 1988) indicate the need for both lossless and lossy image data compression systems. The ranges developed by the subpanel suggest ratios of 2:1 to 4:1 for lossless coding and 2:1 to 6:1 for lossy predictive coding. For the NASA Freedom Science Video Processing Facility it would be highly desirable to implement one baseline compression system which would meet both of these criteria. This paper presents such a system utilizing an LZW hybrid coding scheme which is adaptable to either type of compression. Simulation results are presented with the hybrid LZW algorithm operating in each of its modes.

Introduction:

LZW lossless coding^{1,2} is a completely reversible process; the encoding/decoding operations preserve all of the information contained in the input data sequence. This technique may be used on image data, computer files, or telemetered data. The hybrid system presented in this paper has the ability to compress image data in either a lossless or lossy mode, trading off data quality for data volume. It does this by means of an adaptive DPCM loop, which decorrelates the input image into symbols, before encoding with the LZW algorithm. The DPCM output symbols may be uniquely represented (lossless mode) or quantized (lossy mode.)

In addition, a mechanism is provided for the compression of non-video (telemetered) data. The mode of operation may be selected through the command and control system.

Decorrelating the input image (the decorrelation circuit):

Let S_i represent the value of the i^{th} element of an image vector \mathbf{S} , being clocked out of a camera. The value of the previous pixel is thus S_{i-1} . The "error" vector (sometimes called the difference signal) \mathbf{E} , is defined as $E_i = S_i - S_{i-1}$. A complete, alternate representation of \mathbf{S} is the first pixel, S_0 , followed by the vector of error values, \mathbf{E} . This representation contains enough information to reconstruct \mathbf{S} (since $S_i = S_{i-1} + E_i$.) This idea forms the basis of predictive coding theory³.

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The compression ratio for lossless coding is bounded by the entropy of the input data. Since adjacent pixels in an image tend to be highly correlated, the resulting entropy for the vector **E** is much lower than that of the original vector **S**. **Fig. 1** shows a reconnaissance image (**S**) and its histogram, and **Fig. 2** shows the resulting decorrelated image (**E**) and its histogram. In **Fig. 2** all values of **E** have been made positive by adding an offset. Thus, $E_i=0$ is displayed at the middle of the graph.



Fig 1-1 (Recce. original)

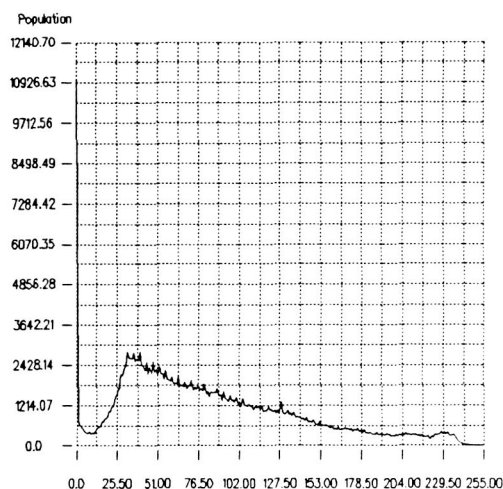


Fig 1-2 (Histogram of Recce. image)

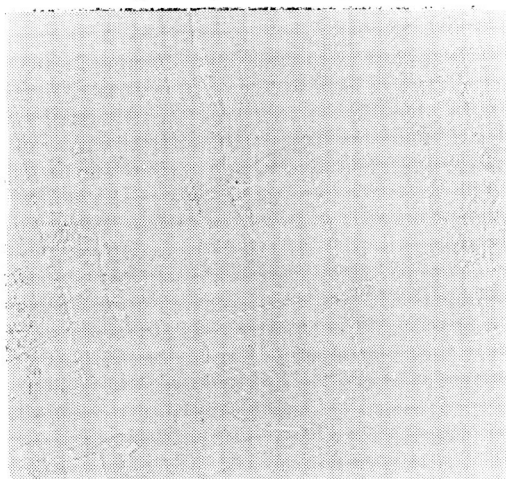


Fig 2-1 (Recce. Decorrelated)

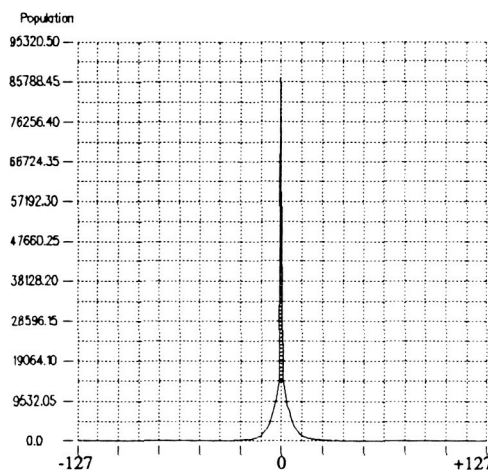


Fig 2-2 (Histogram of Decorrelated image)

Uniquely representing each error value, as in **Fig. 2**, requires 2^{n+1} bits, where n is the total number of bits per pixel in **S**. In this way, all information is preserved and **S** can be completely reconstructed; such a representation is used in the lossless mode of the hybrid LZW compressor.

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BLACK AND WHITE PHOTOGRAPH

Alternatively one can choose to quantize the error signal:

$$E'_i = \left\lfloor \frac{E_i + .5}{\Delta} \right\rfloor \Delta$$

where Δ = the current bin width of the quantizer

and then

$$S'_i = S'_{i-1} + E'_i$$

If $\Delta \geq 2$, then \mathbf{E} can be represented with fewer bits, but quantization error is introduced into the image; this technique is used in the lossy mode of the compressor. The case $\Delta=1$ is referred to as linear quantizing, and represents the lossless mode.

It is possible to switch between the lossy and lossless modes of operation by determining the representation to use to describe \mathbf{E} : either uniquely representing or quantizing each E_i (see **Fig. 3.**) For the remainder of this paper, the error E'_i and error vector \mathbf{E}' , will be used to represent output from the quantizer in **Fig. 3.**

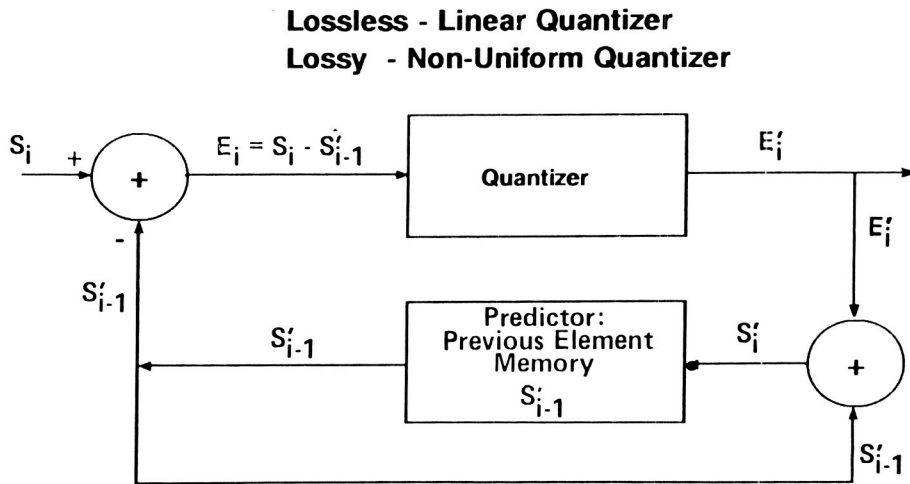


Fig 3. Decorrelation Circuit

Encoding the Error:

Once the quantized error vector \mathbf{E}' is obtained, it is encoded with the LZW algorithm, thus preserving all information contained in \mathbf{E}' . The LZW algorithm is a good choice since it approaches the lower bounds of compression ratios attainable by block-to-variable and variable-to-block codes designed to match specific source data. Since the LZW routine automatically adapts to changes in the source data no *a priori* information about \mathbf{E}' is required.

System block diagram:

Fig. 4 shows the block diagram for the compression system. The image **S** (in **Fig. 4**, shown coming from an experiment occurring in the Space Station) passes through a subtractor which forms **E**. Then, depending on the mode selected, E_i' is formed by quantizing or singularly representing (linear quantizing) E_i .

The "predictor" block in **Fig. 4** is simply a function for improving the accuracy of the value E_i . Instead of representing E_i by $S_i - S'_{i-1}$, some other equation may be used which takes into account the correlation between vertically adjacent pixels in the image. **S** is now represented as a two dimensional array $S_{i,j}$, where i and j have origin at 0 and are bounded by the maximum horizontal and vertical dimensions of the image. Determining good equations for E_i is the subject of many books and papers on predictive coding⁴. The equation used for the remainder of this paper is

$$E_i = S_i - P(i,j) ,$$

where

$$P(i,j) = 0.75 * S'_{i-1,j} - 0.5 * S'_{i-1,j-1} + 0.75 * S'_{i,j-1}$$

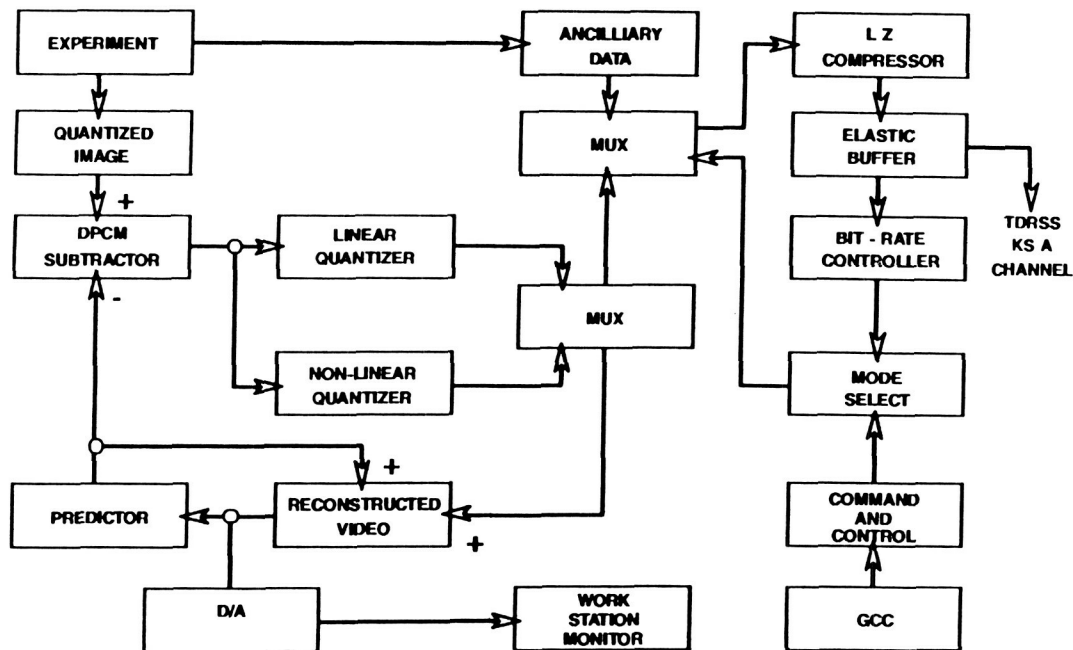


Fig 4. Hybrid LZW system block diagram

After quantizing, the signal E' is fed into the LZW compressor which codes it without loss. The resulting symbols are placed into an elastic buffer (described later), and are finally output into a fixed channel (in **Fig. 4**, the TDRSS KSA channel.)

The elastic buffer and bit-rate controller are shown as two separate blocks (in reality they are often merged.) The purpose of the bit-rate controller is to switch between lossless and lossy modes so that the output symbols from the LZW compressor are of constant rate (in bits/pixel) on average. The bit-rate controller does this by examining the current rate of compression and changing the current mode of operation (lossless or lossy), when necessary, to bring the rate into the desired range.

Additional control is provided by resetting the LZW symbol table when compression falls below the channel output rate. In such a case, symbols are being generated too efficiently. By resetting the LZW table, we force the algorithm to begin learning the scene statistics anew. This results in a lower compression rate until the table fills up.

Unfortunately, the rate out of the LZW encoder cannot be controlled at every instant. Thus, the elastic buffer is needed to hold several lines of image information in case of drastic changes in the scene statistics (which cause a large change in the instantaneous bit-rate.) In this way, constant output rate may be assured over the entire image, if not on a line by line basis.

In addition to compressing image data, the system provides a path for non-image data. This ancillary information (such as data from experiments) is fed directly into the LZW compressor.

Results:

A variety of images were selected to examine the performance of the hybrid LZW compression system in each of its modes. Some results for the lossy mode ($\Delta=8$) are shown in **Fig. 5**. Two of the images, (Docking Target and Satellite) contain significant amounts of tape noise. Lossless results are not shown since the original image is always equal to the reconstructed image. **Tables 1** and **2** show compression of between 3.4 and 4.3 bits/pixel for the lossless mode, and 1.24 to 1.59 bits/pixel in the lossy mode with $\Delta=8$. The quantizer used for the lossy case is a non-uniform quantizer (**Fig. 6**.) For such a quantizer, the width of each bin increases as E_i' increases, and the output of each bin is not its center, but rather its centroid.

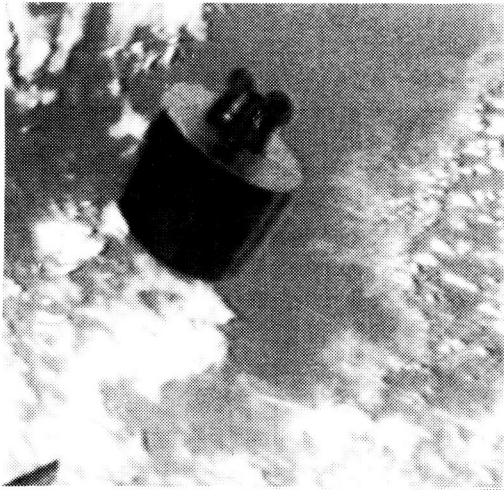


Fig 5-1. Satellite Image

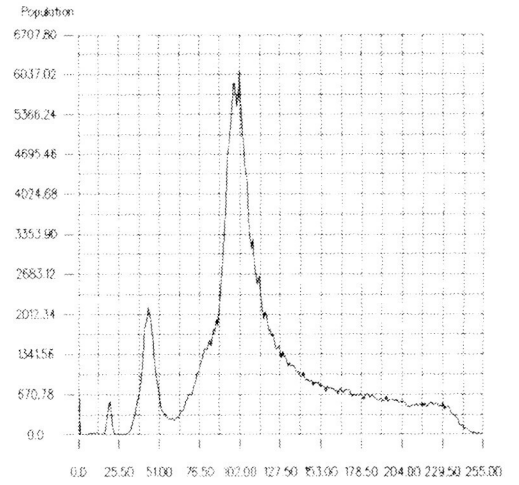


Fig 5-2. Histogram of Satellite

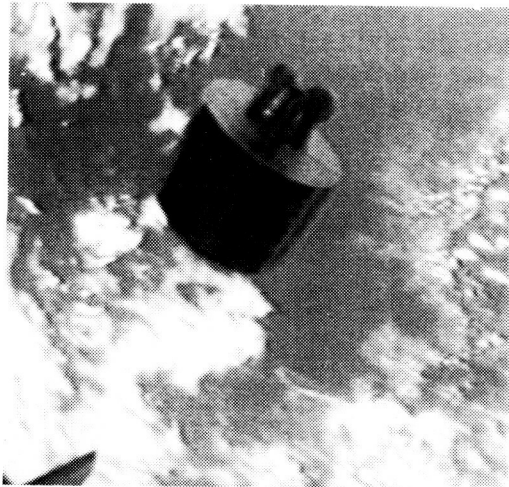


Fig 5-3. Satellite reconstructed with $\Delta=8$

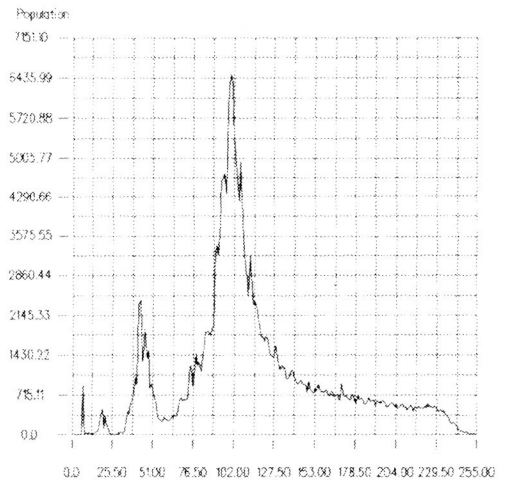


Fig 5-4. Histogram of Fig 5-3.

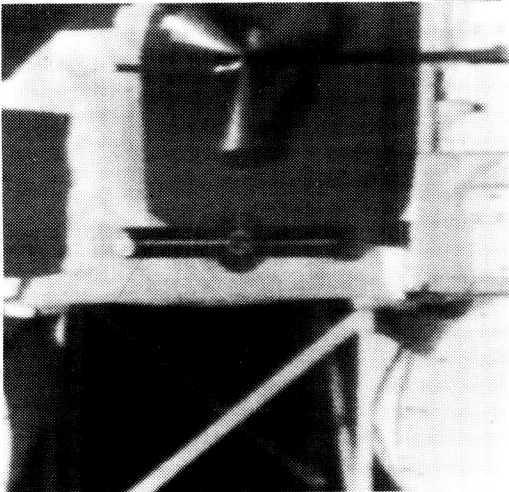


Fig 5-5. Docking Target Image

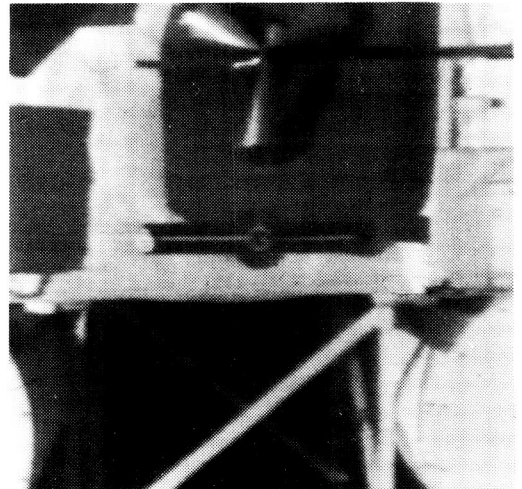


Fig 5-6. Dock. Targ. reconstructed with $\Delta=8$

Lossless L Z Compression

IMAGE	ENTROPY ORIGINAL IMAGE BITS/PIXEL	LINEAR DECORRELATED ENTROPY BITS/PIXEL	L Z COMPRESSION BITS/PIXEL	L Z COMPRESSION RATIO
DOCKING TARGET	7.31	3.61	3.40	2.05
SATELLITE	7.23	4.05	4.3	1.86
CLOUDS	6.38	3.41	3.74	2.13

Table 1. Lossless Compression Results

Non - Uniform Quantizer - Followed By L Z Encoder

IMAGE	ENTROPY ORIGINAL IMAGE BITS/PIXEL	NON-LINEAR DECORRELATED ENTROPY BITS/PIXEL	L Z COMPRESSION BITS/PIXEL	L Z COMPRESSION RATIO
DOCKING TARGET	7.31	1.18	1.24	6.45
SATELLITE	7.23	1.54	1.59	5.03
CLOUDS	6.38	1.24	1.30	6.15

Table 2. Lossy Compression Results

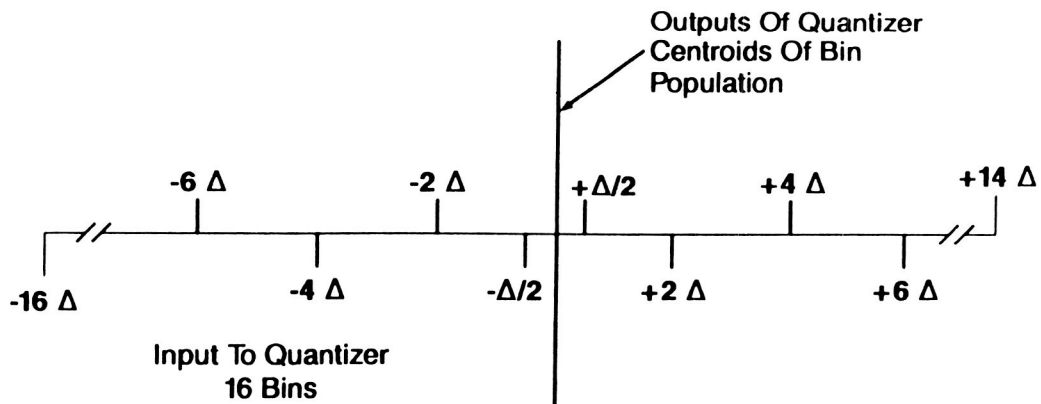


Fig 6. Non-uniform quantizer

Future Plans:

Current results from the hybrid LZW routine indicate that it is possible to satisfy both lossless and lossy requirements in a single system. In order to gain even greater compression ratios, several possible enhancements are currently being investigated.

Improved control of the bit-rate out of the quantizer is being developed for the lossy case. Control is provided by modification of Δ on a line by line basis, that is, the current bit-rate is examined at the end of every line, and Δ is adjusted (if necessary) to raise or lower the output symbols to the desired rate.

Further optimization of the non-uniform quantizer is possible. A constrained loss quantizer should be implemented. This quantizer uses a $\Delta=1$ (linear quantizer) for low values of E_i , and uses larger values of Δ as the values of E_i increase.

Finally, use of the Discrete Cosine Transform to decorrelate \mathbf{S} instead of a DPCM predictor is being considered. LZW compression ratios of 16:1 have been realized for DCT coefficients.

Summary:

A hybrid LZW compression system has been presented which satisfies NASA requirements for both lossy and lossless compression. The system has been simulated on a computer, and has produced good quality output images at rates as low as 1.24 bits/pixel. The system appears to have applicability for spacecraft and reconnaissance imagery.

References:

- [1] A. Lempel and J. Ziv. "A universal algorithm for sequential data compression." *IEEE Trans. Inform. Theory*, IT-23(3):337-343, May 1977.
- [2] Terry A. Welch. "A Technique for High-Performance Data Compression." *Computer*, pp. 8-19, June 1984.
- [3] Arun N. Netravali and Barry G. Haskell. *Digital Pictures Representation and Compression*. Plenum Press, New York, 1982.
- [4] Azriel Rosenfeld and Avinash C. Kak. *Digital Picture Processing*. Academic Press, New York, 1988.